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Review on natural hydrogen wells safety

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Hydrogen is a promising clean energy source with geological reserves widely distributed globally, offering an annual flow exceeding 23 trillion grams. However, natural hydrogen extraction wells face unique safety challenges compared to conventional oil and gas wells. This paper reviews well safety concerns such as tubing/casing damage, cement/sealant failure, and excessive annular pressure buildup. Key issues include hydrogen embrittlement, microbiological corrosion, H_2-cement reaction, and H_2-rubber degradation, which can lead to mechanical failures. The review explores potential solutions like metal coatings, rubber fillers, and cement additives to mitigate these problems. It also emphasizes the need for further research to validate these solutions under real-world conditions. Addressing these challenges is crucial for the safe and efficient extraction of natural hydrogen.

Rapid population growth and industrialization have driven a continuous rise in fossil fuel consumption and globally recognized environmental challenges[1,2]. By January 2023, the global average concentration of CO_2 in the atmosphere reached 416.8 ppm, marking a 135 ppm increase compared to pre-industrial levels and representing the highest value observed in the past 400,000 years[3]. In response to climate change, energy strategies such as diversification of energy sources, development of renewable energy sources, and the exploration of alternative energy carriers have been emphasized by many major energy consumers[4]. Hydrogen is expected as a promising alternative to fossil fuels due to its high energy density and renewable characteristics[5]. Besides the fuel, agriculture, and chemical applications, hydrogen can serve as a versatile medium for energy storage[6]. The combustion of hydrogen produces water with zero carbon emissions, which offers a feasible approach for industrial decarbonization and CO_2 reduction[7,8].

Figure 1a indicates the global hydrogen demand raised to over 94 million tons in 2021[9]. Notably, hydrogen supply only depends on anthropogenically produced hydrogen, with more than 96% sourced from fossil fuels (as illustrated in Fig. 1b)[10]. The anthropogenically produced hydrogen is categorized into gray, brown, blue, and green classes. They are produced from steam methane reforming, liquid petroleum products or coal gasification, carbon capture and storage (CCS) applied to gray or brown hydrogen, electrolysis of water utilizing renewable energy[11], respectively. Steam methane reforming (SMR) remains the most widely utilized and technologically mature method for large-scale hydrogen production, contributing to ~80% of the global hydrogen supply. SMR exhibits a conversion efficiency ranging from 74%–85%, with each kilogram of hydrogen produced generating ~8.5 kilograms of CO_2 emissions[12]. The cost of hydrogen production through SMR stands at $2.08/kg without CCS and rises to $2.27/kg when CCS is implemented[13]. Hydrogen production through coal gasification, with an efficiency of ~58%, incurs a cost of about $1.60/kg, while generating roughly 20 kilograms of CO_2 for every kilogram of hydrogen produced[11]. The environmental impact and the depletion of coal reserves have increasingly directed attention towards renewable feedstocks for future hydrogen production[11]. Although hydrogen produced through electrolysis offers higher purity, operational simplicity, and zero emissions, the significant electricity consumption of electrolyzers has limited its competitiveness in terms of cost when compared to other large-scale technologies. Integration of electrolytic hydrogen production with clean energy sources like wind and solar power converts the surplus electricity during off-peak periods into green hydrogen. It not only utilizes the unstable supplies of renewable energy, but also generates zero carbon emission hydrogens. However, due to infrastructure, storage, and transportation costs, coupled with the substantial electricity expense, the current price of green hydrogen remains considerably high (ranging from $4.15 to $10.4/kg)[4,14]. It is expected that global hydrogen usage will double by 2030 and reach 180 million tons. Therefore, the development of natural hydrogen

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resources is crucial for ensuring economically viable and environmentally friendly hydrogen supplies.

Natural hydrogen is naturally formed and accumulated hydrogen reservoirs. A recent study suggests that certain ophiolites may hold valuable hydrogen gas, presenting potential for extraction[15]. There may be a sufficient reserve of natural hydrogen to meet the continuously growing global energy demands for thousands of years[16]. Compared to fossil fuels, all current methods of hydrogen production remain prohibitively expensive[13]. Extracting hydrogen from underground natural deposits may present a more economically viable alternative, provided that adequate gas capture technologies are implemented[17]. Therefore, the strategic utilization of natural hydrogen could significantly accelerate the development of clean energy. Integrating the development of natural hydrogen with the production of hydrogen from renewable sources could further mitigate the challenges encountered in hydrogen production, as depicted in Fig. 2[10,18,19].

Current research has evidenced the presence of natural hydrogen in various locations worldwide. Discoveries have been made in Oman, New Zealand, Russia, the Philippines, Japan, China, as well as in the western Alps region of Italy and France[20,21]. Natural hydrogen manifests

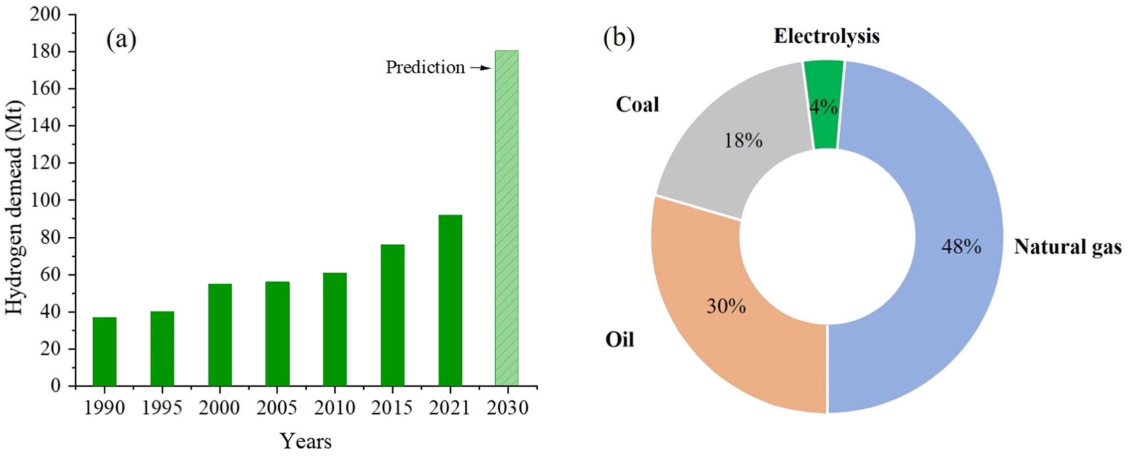

Fig. 1 | Hydrogen demand and current hydrogen sources. a Evolution of hydrogen demand, 1990 – 2030. By 2030, global hydrogen demand is expected to double, reaching ~180 million tons[9]. **b** Hydrogen production from different sources. Currently, 48% of hydrogen is derived from natural gas, 30% from oil, 18% from coal, and only 4% from electrolysis[10]. Figure adapted from refs. 9,10 with permission from Elsevier.

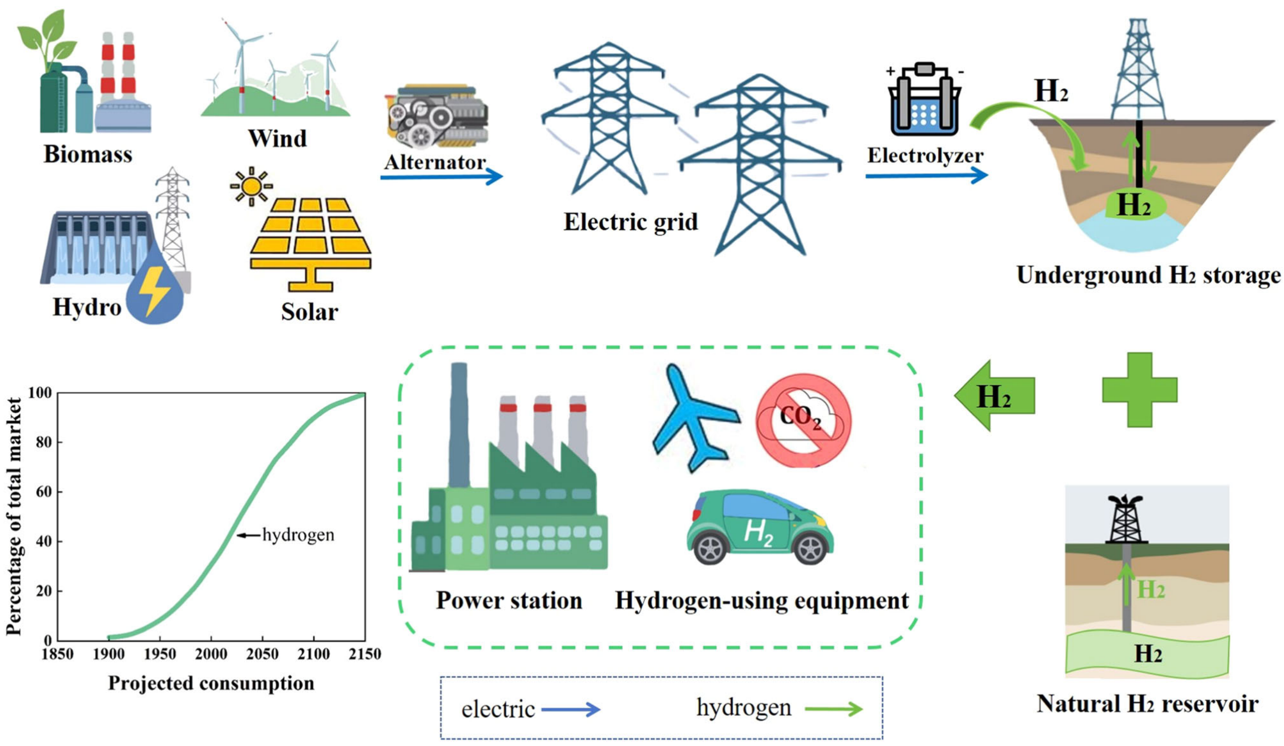

Fig. 2 | Conceptual diagram of integrated utilization of natural hydrogen and renewable energy. By 2150, hydrogen energy is anticipated to emerge as the dominant global energy source. Throughout this transition, renewable energy sources such as wind, solar, and hydropower are poised to play pivotal roles; however, their inherent intermittency presents a significant challenge. Converting electrical energy to hydrogen during periods of low electricity demand can effectively facilitate energy storage and accelerate the development of hydrogen energy infrastructure. Additionally, the safe and large-scale extraction of natural hydrogen in the future is projected to supplement the shortfall in green hydrogen supply, thereby substantially advancing the hydrogen energy transition. Figure adapted from refs. 10,18,19 with permission from Elsevier.

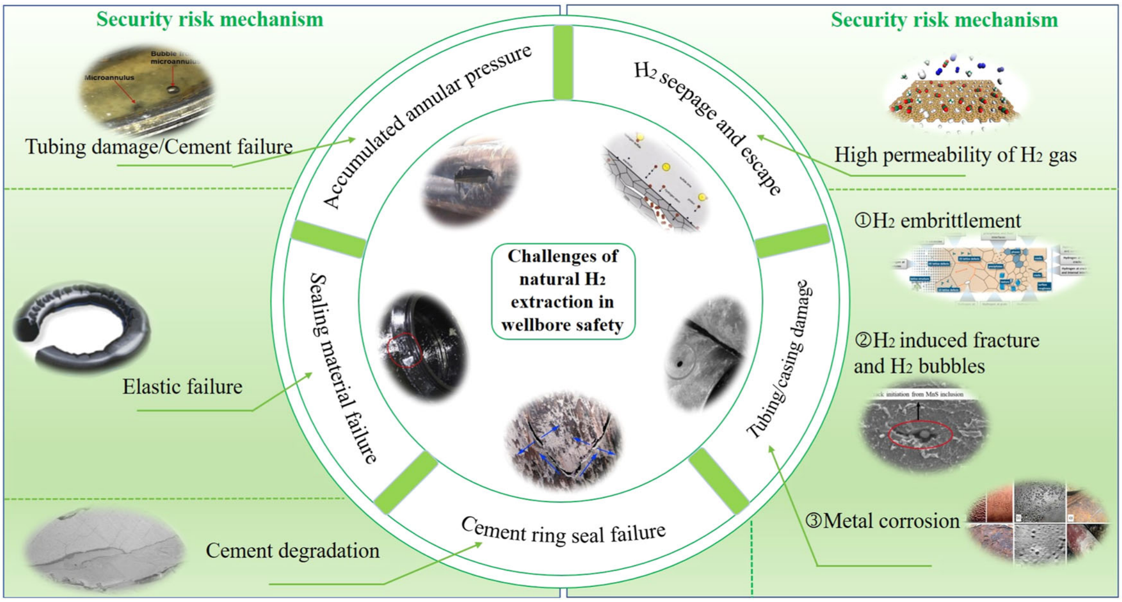

Fig. 3 | Aspects of natural hydrogen extraction well safety. Given the high permeability and specific chemical and biological reactivity of hydrogen, several safety risks are associated with hydrogen extraction wells. These risks encompass tubing/casing damage, cement/sealant failure, and excessive annular pressure buildup. The mechanisms underlying these risks involve hydrogen embrittlement, microbial corrosion, H_2-cement reaction, and H_2-rubber degradation. Figure adapted from Ref. 125 and Ref. 126 with permission from Elsevier, from ref. 127 with permission from Sage Publications, and from refs. 96,128 under a CC BY 4.0 licence https://creativecommons.org/licenses/by/4.0/.

either as surface seepage or sporadic subsurface accumulations[22,23]. This challenges the opinion that underground accumulations of natural hydrogen are absent. Due to high diffusivity, it was previously believed that underground accumulations of natural hydrogen were nonexistent. During past geological explorations such as those for oil and natural gas, the presence of hydrogen may have been overlooked due to the absence of hydrogen-specific detection devices[24]. Even to date, only a minor fraction of portable gas detection equipment is equipped with hydrogen detection capabilities. Additionally, previous oil and natural gas exploration endeavors have predominantly concentrated on sedimentary basins, which may not inherently contain abundant hydrogen[25].

Despite the proliferation of research projects globally investigating natural hydrogen resources, detailed information on quantities, costs, and specific locations is often kept confidential, thereby restricting the data accessible to researchers. Publicly available information indicates that significant progress has been made in the development of the Bourakebougou hydrogen field in Mali, where natural hydrogen has been utilized for power generation in recent years[26]. This success has catalyzed heightened interest among other nations and scholars in the potential of natural hydrogen resources. In May 2022, the European Union announced an target of 20 billion kilograms of natural hydrogen by 2030. The United States drilled its inaugural hydrogen well in 2019, and in September 2022, the U.S. government committed an investment of approximately $700 million towards natural hydrogen exploration[15]. France has established a dedicated natural hydrogen research organization to bolster the field's development, while Australia's Gold Hydrogen Ltd. has identified high-purity natural hydrogen resources on Kangaroo Island and the southern Yorke Peninsula, with plans for exploration, development, and resource estimation. In 2023, The French company La Française de l'Énergie speculated that there could be a high-concentration natural hydrogen deposit in the Lorraine mining area, with an estimated total reserve of up to 46 million tonnes[27].

Although they share some similarities with natural gas wells, technical gaps still exist in the drilling, completion, and production of natural hydrogen wells[28,29]. Based on the experiences of natural gas extraction and CO_2 sequestration industries, ensuring well safety in natural hydrogen extraction is of utmost importance throughout all operational stages. Figure 3 illustrates the potential safety concerns of natural hydrogen wells. The low density and viscosity of hydrogen can cause it to rapidly flow upwards through cement-sealed channels, compromising the integrity of the cement and potentially leading to blowouts. The acid byproducts (H_2S and CO_2) of chemical and biological reactions would trigger corrosions in the wellbore which may lead to safety issues such as tubing/casing damage, cement/sealant failure, and excessive annular pressure buildup[30,31].

Natural hydrogen extraction is an emerging field, with current research into the mechanisms underlying well safety still in its early stages. This review outlines the characteristics of natural hydrogen reservoirs, identifies the key safety challenges associated with wells in hydrogen extraction, and provides a comprehensive summary of hydrogen-induced damage mechanisms that threaten well safety. Afterwards, key directions for future research are proposed.

Characteristics of natural hydrogen reservoirs

Natural hydrogen primarily denotes hydrogen extensively distributed in geological environments like continental crust, oceanic crust, and volcanic hydrothermal fluids, originating from either biological or abiotic processes, thereby exclusively of geological origin. In recent years, researchers have summarized several origins of natural hydrogen, including: (1) the natural radioactive dissociation of deep underground water by radioactive elements in high-radioactivity rocks; (2) the reaction between hot underground water and peridotite during serpentinization, releasing natural hydrogen; (3) deep-seated origins of natural hydrogen generated from the Earth's core or mantle; and (4) fault motion during rock fragmentation and its associated free radical formation[32–34].

Synthesizing the possible origins and distribution of global hydrogen (Fig. 4), it is evident that natural hydrogen sources are widely distributed across major tectonic plates and oceanic crust, predominantly originating from deep-seated sources[35]. The concentration of hydrogen within certain reservoirs is directly correlated with the depth of the strata. Due to the low density of hydrogen, some

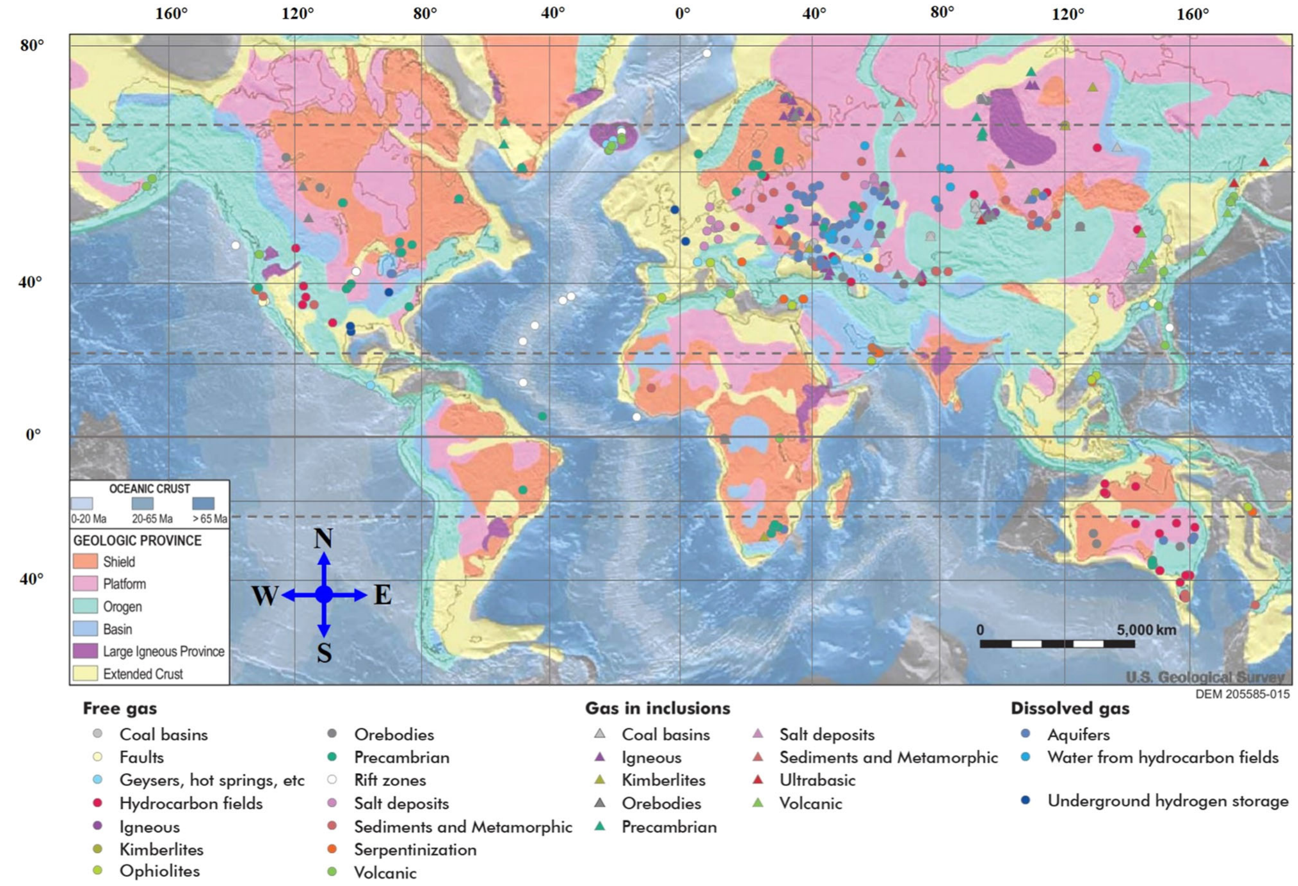

Fig. 4 | Global distribution of natural hydrogen. The location and geologic setting of hydrogen greater than 10% by volume has been measured around the world. The background map illustrates the principal geological zones of the Earth's crust, encompassing the shield crust (orange), platform (pink), orogen (green), basin (blue), large igneous province (purple), and extended crust (yellow), collectively constituting the craton. On these geological formations, various colored circles signify the presence of free hydrogen gas associated with distinct rock types, with the exception of three cases involving dissolved gases. The triangle symbols denote hydrogen gas detected within diverse types of inclusions. The relatively dense distribution of hydrogen discoveries in Europe and Asia is attributable to biases in data collection rather than to an accurate indication of the local prospects for hydrogen molecules. Figure adapted from ref. 35 under a CC BY 4.0 licence. Department for Energy and Mining, the Government of South Australia, Current perspectives on natural hydrogen: a synopsis, sourced on July 2022, https://www.energymining.sa.gov.au/industry/geological-survey/mesa-journal/previous-feature-articles/current-perspectives-on-natural-hydrogen-a-synopsis.

underground hydrogen has the potential to migrate from deep reservoirs to shallower depths through diffusion and advection mechanisms propelled by buoyancy and concentration gradients. Observations of deep-seated serpentinization-derived natural hydrogen leakage in regions such as Russia, Australia, the United States, and Brazil suggest the potential for natural hydrogen migration to shallower geological strata[29]. Moreover, hydrogen is frequently observed in ultra-deep wells (drilled to 5 kilometers or deeper)[36,37]. Traces of natural hydrogen have been discovered in deeper, highly saline fractured aquifers and carbonate formations[38]. The high-temperature, high-pressure conditions of deep geological formations, along with the presence of high-salinity environments and carbonate formations with high hydrogen diffusion rates, pose challenges to the safety of natural hydrogen extraction wells.

Similar to natural gas extraction, drilling remains the primary method of natural hydrogen production. Natural hydrogen reservoirs are confined by impermeable layers and can be accessed by drilling a well. Hydrogen originates from reactions between shallow iron-rich formations and thermal underground water, it can also be extracted by drilling into the iron-rich formations from the surface. Even in instances where there is inadequate thermal underground water to react with iron-rich formations for serpentinization, artificial injection of water into the formation can be utilized to generate adequate concentrations of hydrogen, subsequently extractable through production wells[39]. Wellbores serve as conduits connecting the reservoirs to surface transportation pipelines, making their safety crutial for the secure extraction of natural hydrogen.

Well damage in hydrogen extraction

Current research on natural hydrogen primarily focuses on geological characterization. Although lessons learned from the conventional natural gas wells are valuable, drilling and completion strategies for hydrogen extraction may present challenges due to the unique physical properties of hydrogen. As the smallest molecule in nature, H_2 has exceptionally high diffusivity and permeability in both air and solid materials. The properties of hydrogen with those of CO_2 and CH_4 are compared in Table 1. Its low density, low viscosity, high diffusivity, and chemical/biological reactivity characteristics could introduce new challenges to wellbore safety. Notably, under the influence of overburden pressure, the diffusion capability of hydrogen is further enhanced[40]. The safety of natural hydrogen extraction wellbores is compromised by issues such as tubing/casing damage, cement/sealant failure, and excessive annular pressure buildup. It is crucial to ensure the reliability of well completion devices within the wellbore, including blowout preventers, wellhead equipment, tubulars, packers, valves, outer casings of instruments, and their threaded connections. This section outlines wellbore damage risks encountered in natural hydrogen extraction wells.

Table 1 | Properties of H_2, CH_4, and CO_2[124]

Properties	H_2	CH_4	CO_2
Molecular mass (g/mol)	2.016	16.043	44.009
Density (kg/m^3)	0.08375	0.6682	1.842
Dynamic viscosity at 293.15 K (10^{-5} Pa s)	0.88	1.10	1.47
Specific gravity (air = 1)	0.07	0.55	1.52
Diffusion coefficient in air (cm^2/s)	0.756	0.21	0.16
Solubility in water (g/100 g)	0.00016	0.0023	0.169
Net heating value (kJ/g)	120–141.7	50–55	/

Tubing/casing damage

The degradation and potential failure of steel materials, including tubing and casing. due to hydrogen embrittlement, represent significant limitations in the hydrogen extraction process. This phenomenon imposes a critical constraint on the operation of hydrogen extraction wells[41,42]. Additionally, subterranean microorganisms may exacerbate the corrosion and deterioration of tubing/casing in natural hydrogen extraction wells. Certain natural hydrogen is produced through serpentinization reactions involving iron-rich minerals and subsurface thermal waters. In these environments, the ubiquitous presence of microorganisms should not be underestimated. Notably, sulfate-reducing bacteria (SRB) can induce sulfate reduction reactions, wherein hydrogen is utilized to reduce sulfate (SO_4^{2-}) or sulfur to hydrogen sulfide (H_2S). The resulting H_2S can corrode steel and other metals, thereby compromising the integrity of wellbore tubing/casing[43].

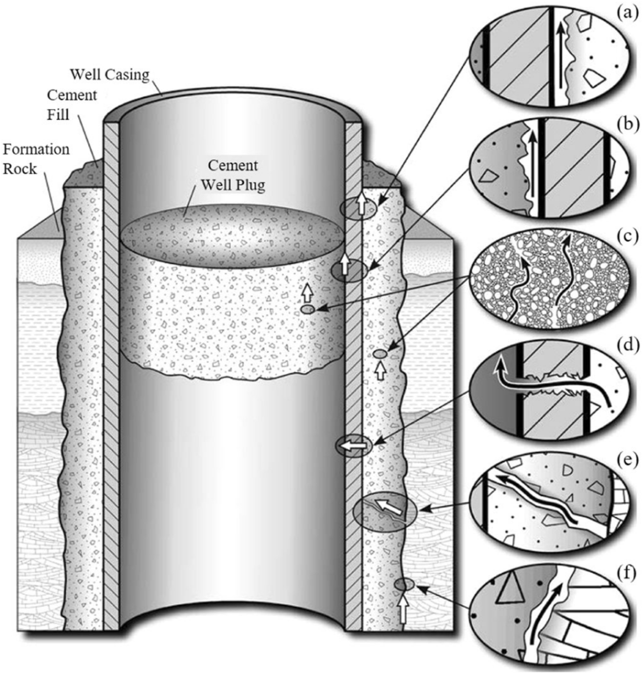

Fig. 5 | Potential leakage paths in the wellbore. a between the casing exterior and the cement, **b** between the cement plug and the casing interior, **c** the cement plug, **d** the casing wall, **e** the cement cracks, and **f** between the cement and the formation. Figure adapted from ref. 129 with permission from Springer Nature.

Cement failure

Wellbore cement functions as a mechanical barrier, mitigating the risk of uncontrolled gas migration to the surface or annulus. However, studies have demonstrated that during prolonged well operation, various factors can contribute to the degradation of cement, thereby undermining its integrity and durability. Specifically, the physical properties of hydrated products in Portland cement can be altered when exposed to CO_2-rich fluids, leading to changes in compressive strength[44,45]. Existing research indicates that in a hydrogen environment, wet cement can generate gas bubbles, and its rheological properties, mechanical strength, and stability may be adversely affected[46]. Hydrogen can modify the overall porosity and permeability of casing-cement-formation composite samples[47]. Figure 5 illustrates potential pathways for gas leakage along the wellbore, where cement degradation, micro-annuli at the casing-cement-formation interface, fractures within the cement sheath, and casing defects could all contribute to hydrogen leakage.

Sealant failure

Elastomeric sealing elements are extensively employed in standard wellbore equipment, including wellhead components, packers, downhole safety valves, and blowout preventers. These devices are primarily designed to isolate fluids within the casing, tubing, and annulus. Failure of elastomeric sealing components can result in uncontrolled direct pathways between fluids and the surface or formation, potentially leading to catastrophic events like blowouts. Research suggests that gases such as CO_2, H_2S, and hydrogen can significantly degrade the performance of elastomeric materials, potentially compromising the integrity of packers. Excessive hydrogen content in sealing rubber materials may lead to blistering and subsequent fractures in the sealing material.

Excessive accumulation of annular pressure

The phenomenon of annular pressure buildup refers to the re-establishment of annular pressure in gas wells to pre-bleed levels shortly after depressurization. Annular pressure exerts additional stress on the casing, potentially resulting in casing failure and compromising well safety[48]. In the context of natural hydrogen extraction wells, tubing damage and cement failure often lead to annular pressure buildup, leaving the production casing above the packer vulnerable to hydrogen-induced corrosion. Consequently, the service life of production casings encounters notable challenges arising from the interplay between corrosion and annular pressure buildup[49].

The mechanisms of hydrogen-induced wellbore damage

This section focuses on hydrogen-induced damage mechanisms that create wellbore damage risk, including hydrogen embrittlement, microbiological corrosion, H_2-cement reaction and H_2-rubber degradation. Laboratory findings on material susceptibility to these mechanisms are reviewed, and corresponding research results are analyzed. Advances in technology aimed at mitigating wellbore safety risks are also discussed.

Hydrogen embrittlement

Hydrogen molecules collide with and adsorb onto the surface of steel, subsequently diffusing into the steel in atomic form. It leads to various hydrogen-induced damage in the wellbores, including hydrogen embrittlement, hydrogen-induced cracking, and hydrogen blistering of the steel[41].

Due to the small size of hydrogen atoms, when they diffuse into or dissolve within steel and reach a critical concentration, they can accumulate and lead to a significant reduction in the ductility and tensile strength. This process may result in premature material failure, often manifesting as brittle fracture under stress[42]. Typically, hydrogen embrittlement causes a marked decrease in the material's toughness, plasticity, and fatigue strength, shifting its fracture behavior from ductile to brittle. This shift may cause tubing and threaded connections failure[43,50,51].

An effective explanation for metal failure modes is the Hydrogen-Induced Decohesion (HID) mechanism. The Hydrogen-Enhanced

Localized Plasticity (HELP) theory explains the loss of metal strength in the presence of hydrogen by suggesting that local deformation near the crack tip is accentuated. The diffusion of hydrogen increases dislocation mobility due to diminished metal resistance[52]. Consequently, the introduction of hydrogen rapidly accelerates dislocation movement, leading to plastic deformation within the metal lattice. Besides, the Hydrogen Pressure Theory, Hydrogen-Enhanced and Strain-Induced Vacancies, and Hydrogen-Enhanced Macroscopic Ductility, also provide insights into the damage mechanisms of hydrogen embrittlement in metals. The determination of the predominant damage mechanism should be analyzed based on specific circumstances[53].

Hydrogen that enters the material can be diffusible or trapped. Diffusible hydrogen causes hydrogen-induced damage, resulting in a reduction in material performance, whereas trapped hydrogen is not expected to contribute to plastic deformation in materials[54,55]. The factors affecting HE primarily include environmental conditions, material sensitivity, and loading conditions. Environmental factors include hydrogen concentration/purity, pressure, and temperature. Loading factors consist of applied mechanical or thermal stresses, strain rate, and the frequency and amplitude of loads. Material susceptibility is influenced by factors such as composition strength, residual stress in the material, microstructure, surface condition of the material, metallic coatings, heat treatment of materials, metallic coatings[50,56]. Metal damage occurs at low concentrations could be reversible, whereas high concentrations can lead to permanent damage. The presence of H_2S in hydrogen gas exacerbates this damage. Temperature affects the diffusion coefficient of hydrogen, and high pressure increases the material's sensitivity to hydrogen embrittlement. Higher applied stresses and lower strain rates can also enhance the sensitivity of steel to hydrogen embrittlement.

Extensive studies have investigated the impacts of material strength, microstructure, residual stress, heat treatment, and metallic coatings, on the material's susceptibility to hydrogen embrittlement. Heat treatment can reduce this susceptibility to some extent, as retained austenite in steel contributes to lower sensitivity[57]. Residual stress can induce non-uniform stress distributions within the material, thereby increasing its vulnerability to hydrogen embrittlement[58]. Metallic coatings can alleviate hydrogen embrittlement by partially shielding the metal from hydrogen, though their effectiveness is contingent upon the coating's integrity[50]. Although polymer coatings have low hydrogen permeability, they are prone to failure under high mechanical stress. Ceramic coatings are similarly attractive due to their low hydrogen permeability[59]. An alternative approach to mitigate hydrogen embrittlement sensitivity involves optimizing the alloy's microstructure and components. However, during long-term natural hydrogen extraction, extreme high-temperature and high-pressure gas conditions may alter the hydrogen embrittlement sensitivity of steel, and fluctuating pressures due to unstable gas flow can also affect stress distribution within tubing/casing. Furthermore, in the context of natural gas extraction, the integrity of tubing/casing coatings under prolonged high-velocity gas erosion, as well as the performance of various coating methods under actual downhole temperature and pressure conditions, requires close attention.

The hydrogen embrittlement behavior of steels, especially their mechanical properties, has been extensively studied experimentally. Nanninga et al.[60] and Moro et al.[61] conducted slow strain rate tensile tests on X100 and X80 steels, respectively, in pure hydrogen environments. The results indicate that as hydrogen pressure increases, the reduction in area and elongation at fracture of the materials decrease, and the fracture behavior transitions from ductile to brittle. Trautmann et al.[62] exposed steel to both dry and humid hydrogen atmospheres over a 30-day period, demonstrating that the hydrogen content in steel rises proportionally with hydrogen pressure. Eichinger et al.'s experimental results revealed that, following hydrogen charging at 25 °C, the hydrogen content in P110 steel samples increased linearly with the square root of the applied hydrogen partial pressure. As hydrogen pressure increased from 100 to 1000 bar, the hydrogen content in the steel rose from 0.26 wt.-ppm to 1.0 wt.-ppm. Under conditions of 200 °C, the hydrogen content in P110 increased from 0.47 wt.-ppm at 100 bar to 1.36 wt.-ppm at 1000 bar[63]. Temperature exerts a substantial influence on the susceptibility of materials to hydrogen embrittlement. Xu et al.[64] demonstrated that hydrogen diffusion rates increase significantly with rising temperature, with desorption spectroscopy (DS) spectra indicating the highest hydrogen desorption at 60 °C and the lowest at 20 °C. Xu et al.[64] further compared diffusion coefficients across multiple studies under electrochemical hydrogen charging, consistently finding increased diffusion rates at elevated temperatures. Similarly, Xing et al.[65] reported that within a temperature range of 275 K to 315 K, the steady-state hydrogen permeation current density increases linearly with temperature.

Therefore, the hydrogen embrittlement characteristics of different types of steel are positively correlated with pressure and temperature. Some deep natural hydrogen extraction wells operate under high-temperature and high-pressure conditions, which are not typically addressed in most experimental studies on the hydrogen embrittlement characteristics of steel. Despite significant efforts to reduce hydrogen embrittlement sensitivity, mitigation strategies under downhole conditions demand further investigation. It is also crucial to develop effective hydrogen damage mitigation and monitor strategies based on observed embrittlement in tubing/casing at hydrogen extraction sites.

The concentration of hydrogen influences the susceptibility of steel to HE. Generally, higher pressure elevates the probability of hydrogen atom decomposition at the material surface and penetration into the material, thereby promoting HE[66]. The hydrogen pressure encountered by casing in natural hydrogen extraction wells may differ from that in gas transmission pipelines. Further research is needed to investigate the sensitivity of materials under different pure hydrogen pressure conditions.

Hydrogen induced cracking (HIC) and hydrogen blistering (HB) are phenomena observed in medium to low-strength steels, arising from the precipitation of gaseous hydrogen molecules within cracks. These cracks are typically associated with microstructural features such as planar defects and are generally oriented parallel to the steel surface. When the concentration of atomic hydrogen within the material exceeds its solubility limit, hydrogen atoms in the lattice aggregate to form gaseous hydrogen[67]. The cracks propagate due to the continual accumulation of gaseous hydrogen. Cracking halts when there is inadequate hydrogen infiltration into the material to sustain pressure within the crack. Hydrogen-induced cracking usually appears as progressive cracking or blistering, the latter causing visible defects on the metal surface.

The presence of hydrogen atoms within the metal lattice can lead to the loss of ductility in the metal[68]. When HE occurs in metals, fracture typically necessitates the application of force, with no concurrent precipitation of hydrogen within the material. Subsequent to HE, the removal of hydrogen from the material can restore its ductility, rendering it a reversible process, and the internal damage caused by HIC is irreversible. In contrast, the parameters conducive to HE are more diverse. HIC predominantly manifests under specific aqueous conditions, often associated with the presence of electrochemical charges or H_2S. Research indicates that controlling crystallographic texture and boundary character can effectively reduce the probability of hydrogen-induced cracking. However, the mechanisms involved may change under high-temperature and high-pressure conditions, necessitating further studies to address hydrogen-induced cracking in materials under actual downhole conditions[69,70].

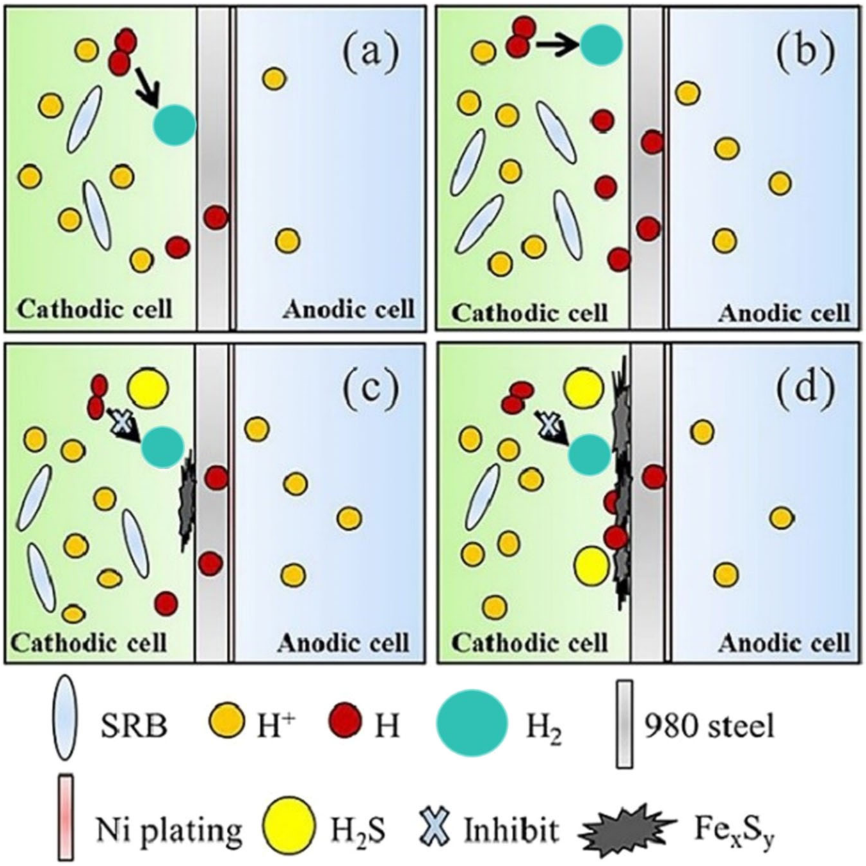

Fig. 6 | Schematic diagram of the effect of SRBs on hydrogen permeation in steel. a After 3 h of SRBs incubation, the number of SRBs is relatively low, leading to most hydrogen atoms combining to form hydrogen, with only a small amount permeating into the steel. **b** After 6 h of SRBs incubation, the SRB population increases, and the sulfate reduction process enhances the cathodic reaction, generating a large number of hydrogen atoms, with more hydrogen permeating into the steel. **c** After 11 days of SRBs incubation, the formation of sulfides on the sample surface inhibits the combination of hydrogen atoms, thereby promoting their diffusion into the steel. **d** After 16 days of SRBs incubation, the SRB metabolism produces H_2S, and a corrosion film of FeS and FeS_2 forms on the steel surface, which partially inhibits hydrogen permeation. Figure adapted from ref. 83 with permission from Elsevier.

Numerous factors influence the corrosion of downhole casing and tubing, such as the presence of H_2S and CO_2 in the formation, the material composition of the tubing, the presence of water production in the gas well, the accumulation of liquids at the well bottom, and the use of corrosion inhibitors. Research indicates that H_2S, CO_2, and chloride ion (Cl^-) can also contribute to gas well corrosion[71,72]. It is important to note that during natural hydrogen extraction, metal components like casing are exposed not only to corrosive conditions but also to the detrimental effects of hydrogen. The behavior of hydrogen embrittlement under corrosive conditions could pose new challenges to well safety in natural hydrogen production.

Microbial activity

The treatment of microbial corrosion is costly in the oil and gas industry, accounting for 20–30% of all internal pipeline corrosion spends[73–75]. Microbial corrosion is defined as an electrochemical process in which microorganisms initiate, promote, and accelerate corrosion reactions through interactions with metals and solutions[76,77]. SRBs are believed to play a significant role in the corrosion of iron alloys. SRBs induce corrosion by cathodic depolarization through an enzyme called hydrogenase, which oxidizes hydrogen at the cathode. During this process, metals dissolve into cations, while hydrogen undergoes reduction at the cathode to maintain dynamic equilibrium in the system. SRBs consume cathodic hydrogen, producing sulfides.

Consequently, SRBs expedite the anodic dissolution of iron (Fe) via the cathodic depolarization mechanism, facilitating the ingress of additional hydrogen atoms into the metal. This process culminates in the formation of corrosion byproducts such as iron sulfide (FeS) and ferrous hydroxide ($Fe(OH)_2$)[78–80]. The description of iron corrosion induced by SRBs is illustrated in Fig. 6 Both SRBs and their metabolic by-products significantly affect the permeation of hydrogen into steel, with the duration of SRBs activity markedly influencing on the hydrogen permeation process[81–83]. Methanogenic bacteria can act in conjunction with SRBs to accelerate the corrosion rate[84]. Other microbial activities, such as acetogenesis and iron reduction, may likewise contribute to the corrosion of steel, thereby compromising its structural integrity[85].

Tremosa et al.[86] conducted numerical simulations to investigate the processes of underground hydrogen storage in porous media. The results of the study indicated that microbial activities, including methane generation, sulfate reduction, and acetogenesis, contribute to hydrogen consumption in underground hydrogen storage reservoirs. Sulfate reduction has a minimal effect on hydrogen content but leads to H_2S production and related corrosion issues. The study underscored the significance of incorporating microbial kinetics into the assessment of redox reactions involving hydrogen as an electron donor. Nevertheless, current research fails to quantitatively established the rates of microbial activity kinetics, highlighting the necessity to extrapolate laboratory-derived redox reaction rates to conditions encountered in reservoirs.

In addition, H_2S produced by microbial activity can induce metal corrosion. In contrast to natural gas, hydrogen acts as an electron donor and constitutes a substantial driving factor for microbial activity[87,88]. Within subterranean hydrogen reservoirs, SRBs consume hydrogen, yielding H_2S as a byproduct. H_2S, an acidic compound, corrodes steel and metal casings, thereby inducing stress cracking[89,90]. Haddad et al.[91] conducted simulations of 10% hydrogen and methane storage in an aquifer using a high-pressure reactor. The study results showed that within less than 90 days of simulating the storage of natural gas in an aquifer, nearly 40% of the injected hydrogen was converted into H_2S, formates, and methane due to microbial activity, and dissolved in the aqueous phase. To comprehend the magnitude and kinetics of hydrogen consumption by microorganisms in high-salinity cave environments, Dopffel et al.[92] conducted experimental research into the proliferation and hydrogen consumption of SRBs and halophilic methanogens at various hydrogen partial pressures. The results demonstrated that SRBs and methanogens could consume substantial quantities of hydrogen over time. Furthermore, the pH of the system increased significantly over time, reaching a maximum value of 9.

Microorganisms and their by-products in hydrogen-rich environments can significantly corrode wellbores. SRBs can grow at temperatures as high as 113 °C and under conditions where the pH exceeds 10. This suggests that SRBs may also inhabit deep natural hydrogen reservoirs characterized by high temperatures and pressures, which differ significantly from those in underground hydrogen storage facilities. Therefore, the growth of microorganisms and cathodic reduction reactions in natural hydrogen extraction wells, as well as the impact of H_2S and other by-products on metal corrosion throughout the extraction lifecycle, require further investigation. Currently, conclusive research on these aspects is lacking.

Based on the oil and gas industry experiences, there are methods to prevent microbial-induced corrosion (MIC) in wellbores, including the use of biocides, antimicrobial coatings, material selection, and cathodic protection. Biocides can effectively prevent and control MIC, although their effectiveness may be limited by operational conditions[77]. Non-toxic compounds like epoxy resins, silicones, and other fluorinated coatings can also offer protection against microbial corrosion. However, like hydrogen embrittlement coatings, the integrity of these coatings is crucial; defects can make them more susceptible to corrosion[93]. The reactivity of these coatings with hydrogen and their stability under high-temperature and high-pressure conditions are important considerations, as degradation may occur. Choosing appropriate materials can significantly mitigate corrosion, but it should be used in conjunction with other methods such as coatings and biocides. Cathodic protection can be effective in preventing corrosion, although its implementation in deep wells can be challenging. Overall, a combination of suitable materials and coatings is likely to be the primary means of preventing corrosion in subsurface tubing/casing of natural hydrogen extraction wells.

H_2-cement reaction

During the extraction of natural hydrogen, the hydrogen comes into contact with the surrounding cement of the wellbore. Previous studies has indicated that hydrogen interacts with cement, causing alterations in its physical properties[94]. According to API specifications, industrial cements suitable for downhole conditions, including the depth, pressure, and temperature, are primarily categorized into classes A to H, with Class G being the most widely used[95]. These cements typically consist of lime (CaO), silica (SiO_2), alumina (Al_2O_3), iron oxide (Fe_2O_3), and gypsum ($CaSO_4 \cdot 2H_2O$). The raw materials undergo a sequence of hydration reactions to produce the four primary compounds that make up Portland cement: tricalcium aluminate ($Ca_3Al_2O_6$ or C_3A), tricalcium silicate (Ca_3SiO_5 or C_3S), tetracalcium aluminoferrite ($Ca_4Al_2Fe_2O_{10}$ or C_4AF), and dicalcium silicate (Ca_2SiO_4 or C_2S)[96].

Hydrogen does not directly react with cement but requires conversion to H^+ for interaction. Thus, the key to the hydrogen-cement reaction lies in the availability of sufficient hydrogen in the environment to convert into H^+[97]. Equations (1)-(4) describe the basic thermodynamic reactions of cement minerals with H^+. Geochemical simulations suggest that hydrogen can reduce sulfates and iron in cementitious materials to sulfides and ferrous compounds, leading to the precipitation of oxidized minerals and iron sulfides.

$$Ca_3SiO_5 + 6H^+ = SiO_2 + 3Ca^{2+} + 3H_2O \tag{1}$$

$$CaCO_3 + H^+ \leftrightarrow Ca^{2+} + HCO_3^- \tag{2}$$

$$Ca_4Al_2Fe_2O_{10} + 2OH^+ \rightarrow 4Ca^{2+} + 2Al^{3+} + 2Fe^{3+} + 10H_2O \tag{3}$$

$$Fe_2O_3(s) + 4H^+ + H_2 = 3H_2O + 2Fe^{2+} \tag{4}$$

Single-celled organisms such as SRBs are known to thrive in subsurface hydrogen environments, consuming hydrogen and producing H_2S in sulfur-rich environments. Cement is susceptible to chemical degradation caused by corrosion from H_2S[98]. Sulfate reactions can lead to the formation of ettringite ($Ca_6(Al(OH)_6)_2 \cdot (SO_4)_3 \cdot 26H_2O$). Ettringite expansion within the cement structure induces internal stresses, leading to cracking[99,100].

Investigating the interaction between hydrogen and cement, as well as understanding the degree of hydrogen-induced degradation of cement, holds significant importance. Ugarte et al.[101] conducted experiments to investigate the interaction between hydrogen and Class H cement, exposing cement samples to hydrogen for 7, 28, 84, and 168 days. The results show that after a certain duration of hydrogen exposure, the compressive strength of cement samples increases, while porosity and permeability decrease. After 168 days, porosity and permeability were reduced by 6.1% and 4.2%, respectively, while Young's modulus and shear modulus increased by 4.7% and 5.0%, respectively, and Poisson's ratio decreased by 1.4%. Composition analysis indicated an increase in the formation of potassium feldspar and calcium feldspar in cement due to the presence of hydrogen, leading to alterations in the distribution of cement porosity and thereby enhancing its mechanical strength. Maury et al. [102] conducted experimental investigations to evaluate the performance changes of Class H cement after exposure to hydrogen under conditions of 10 MPa and 49 °C for 7 and 14 days. Results indicated that after 14 days of exposure, the cement samples' permeability increased by 175% and porosity by 1.9%, contradicting the findings of Ugarte et al. The Young's modulus and Poisson's ratio of the cement decreased by 2.5% and 0.6%, respectively, indicating that hydrogen exposure may lead to a loss of the cement's sealing capacity and structural integrity.

Aftab et al.[96] conducted experimental research on the changes in cement particles after exposure to hydrogen under conditions of 80 °C and 3000 psi for 7 and 14 days. The results showed that chloride ions dissolved in salt solutions may accelerate the hydration reaction mechanism, resulting in a reduction in the contact area between cement particles and water, consequently reducing the probability of chemical reactions occurring in the system. However, under the experimental conditions, hydrogen did not cause any geochemical or structural alterations in the tested wellbore cement. Consequently, Aftab et al.[96] concluded that the impact of hydrogen on cement integrity within salt caverns and porous reservoirs could be insignificant. It is crucial to acknowledge that Aftab et al. pulverized the cement into fine particles to amplify the reaction between hydrogen and cement, potentially neglecting the broader implications of hydrogen on the overall permeability, porosity, and elastic modulus of cement blocks.

In another study, Al-Yaseri et al.[94] conducted hydrogen injection experiments on two Class G cement cores for 125 days under conditions of 1400 psi and 75 °C, assessing the impact of hydrogen on cement integrity. The XRD results revealed a slight rise in the alite content in the cementitious matrix following hydrogen injection, while the growth of calcite was attributed to the cement hydration process. After hydrogen injection, both the mass and density of the cement increased, with the CT-measured porosity of the two samples decreasing by 8.86% and 8.43%, respectively. Their findings also indicated a minor decrease in the permeability of cement paste in a hydrogen atmosphere, accompanied by marginal increases in both the Poisson's ratio and dynamic Young's modulus.

Hussain et al.[46] experimentally investigated the effect of hydrogen on the properties of cured cement blocks and cement slurries under condition of 1500 psi at 120 °F for 7 days. The results indicated that in cement slurry systems, certain amounts of hydrogen become entrapped within the cement, resulting in a reduction in cement strength and an increase in the viscosity of the cement slurry. CT scan images revealed the presence of hydrogen-induced cracks in cured cement, resulting in reduced compressive strength of the cement exposed to hydrogen. Jacquemet et al.[103] conducted simulation studies on the geochemical reaction between hydrogen and Class G cement. The results showed that cement minerals such as ettringite and hematite undergo reductive dissolution, resulting in the formation of iron sulfide and oxide minerals. These dissolution-precipitation reactions do not significantly affect cement porosity due to the limited quantities involved. An increasing number of researchers are focusing on the interaction between hydrogen and cement. Existing studies primarily address the conditions relevant to underground hydrogen storage, without considering the impacts associated with the depth of natural hydrogen reservoirs. Current experiments have demonstrated the effects of temperature, pressure conditions, and reaction duration on hydrogen-cement interactions. Further expansion and refinement of experimental investigations are needed to align with the practical conditions of underground wells. During the long-term interaction between hydrogen and cement, the metabolic activities of hydrogen-oxidizing microorganisms and other kinetic behaviors also influence the process. Therefore, the geochemical reaction simulation of hydrogen with Class G cement needs to account for more complex conditions.

Hydrogen molecules could diffuse and migrate within the cement sheath of the wellbore, potentially resulting in gas leakage. Dudun et al. [31] numerically solved the second-order parabolic partial differential equations describing hydrogen diffusion in cement, utilizing the finite difference method. Simulation results suggest that under anticipated well conditions, complete hydrogen penetration through a 35-centimeter cement sheath would take ~7.5 days. Once hydrogen penetrates the cement sheath and subsequent arrival at the annulus, the risk of leakage increases. Simulation results indicate that hydrogen diffusion rate in cement increases with increasing cement porosity and diffusion coefficient, while it declines with increased water saturation. Consequently, cement characterized by lower porosity is more effective in sealing hydrogen.

The impact of hydrogen on cement properties is substantial; however, inconsistencies in existing research regarding its influence patterns highlight the need for further experimental studies to better elucidate changes in cement properties under natural hydrogen storage conditions. However, existing experimental conditions for hydrogen-cement reactions have only extended up to 168 days, which is considerably shorter than the operational lifespan of natural hydrogen extraction wells. Current research indicates that prolonged exposure may result in alterations to cement properties, including permeability, Young's modulus, shear modulus, and Poisson's ratio[101]. Simultaneously, under the high-pressure and high-temperature conditions prevalent deep underground, the oxidative reactions between hydrogen and cement may intensify. Current research also lacks the inclusion of a broader range of cement types. Factors such as the temperature, thermal conductivity, and pH may also affect hydrogen-cement interactions. Therefore, it is imperative to extend the timescale of experiments to match the operational lifespan of natural hydrogen wells and to broaden experimental temperature and pressure conditions to simulate deep underground high-temperature, high-pressure environments.

The stability of cement sealing is crucial for ensuring the safety of natural hydrogen extraction wells, and it primarily depends on characteristics such as the permeability, thickening time, and unconfined compressive strength. Chemical additives represent a key strategy to improve cement seal integrity. These additives include retarders, accelerators, fillers, lost-circulation materials, dispersants, gas migration inhibitors, expanding agents, and chemical degradation products[104]. However, no studies have yet been reported on mitigating the effects of hydrogen on cement using these additives. In other domains of well safety research, the impact of CO_2-containing fluids on cement integrity has been extensively evaluated. Several studies have demonstrated that the incorporation of supplemental additives (such as nanoclay particles, olive waste, graphite, and synthetic polypropylene fibers) into cement can mitigate the effects of CO_2-containing fluids[44,105–107]. For the cement integrity of natural hydrogen wells, additives present a promising solution. Current research on the impact of hydrogen on cement performance is both limited and inconsistent, with the underlying mechanisms remaining inadequately understood. A deeper understanding of the mechanisms by which hydrogen degrades cement paste could be instrumental in identifying more effective supplemental additives.

H_2-rubber degradation

Seals within wellbores play a critical role in isolating casing, tubing, and fluid in the annulus, typically consisting of elastic materials such as rubber or polymers in conjunction with steel. Seals form essential safety barriers for upholding well control, with their effectiveness in sealing largely dependent on the utilization of non-metallic elastic materials that are nearly incompressible in volume. In conventional oil and gas extraction fields, the research has shown that elastomer failure can occur due to gas pressure fluctuations, chemical degradation, extrusion, erosion, abrasion, compression, and spiral failure. Moreover, hydrogen, due to its unique properties, can affect the performance of both elastomeric and steel materials, thereby compromising seal integrity. Previous studies have demonstrated that high permeability of hydrogen in elastomeric sealing materials exceeds that of natural gas[108].

Natural rubber demonstrates relatively inferior sealing performance against hydrogen compared to other elastomeric materials, exhibiting a permeation rate ~30 times higher[109]. Research conducted by Melaina et al. on hydrogen permeation at mechanical junctions revealed that the hydrogen permeation rate at these junctions is three times that of natural gas[110]. When hydrogen infiltrates non-metallic sealing materials, it may lead to hydrogen absorption swelling or hydrogen blistering phenomena, resulting in material degradation[111]. Hydrogen absorption swelling in non-metallic sealing materials refers to the phenomenon of rubber expansion caused by the dissolution of external hydrogen into the rubber material, while hydrogen blistering is caused by the formation of cracks within the rubber due to rapid pressure reduction of high-pressure hydrogen[112]. Yamabe et al. [113] has elucidated that the swelling of nitrile rubber due to hydrogen absorption correlates with hydrogen pressure or concentration of hydrogen absorption within a pressure range spanning from 0.7 to 100 MPa.

Tetteh et al.[114] experimentally investigated the effect of different gas mixtures on the physical and mechanical properties of three common elastomers: ethylene-propylene-diene rubber, fluoroelastomer, and nitrile rubber. The results revealed that exposure of elastomers to gaseous hydrogen environments resulted in changes in their physical and mechanical properties, leading to material failure. This is primarily attributed to elastomer chain breakage or cross-link formation induced by the plasticizing effect and chemical aging of gases. Polyamide fillers have been demonstrated to enhance the performance of elastomers in high-pressure hydrogen environments. A self-healing elastomer featuring dopamine groups as dangling groups shows promising mechanical properties, with a fracture stress of 1.9 MPa and strong adhesion strength. However, its efficacy in actual underground conditions remains unproven. Nevertheless, it offers a potential approach for investigating the performance of elastomers of various materials under in-situ downhole conditions. The in-situ conditions of natural hydrogen formation are characterized by corrosive agents and extreme temperature and pressure, creating a challenging environment for the long-term performance of elastomers. It is essential to investigate the impact of hydrogen on the physical and mechanical properties of elastomers under conditions of pressure cycling, extrusion, abrasion, and spiral degradation.

Recommendations for the futures works

Although natural hydrogen in regions like Mali has been utilized for electricity generation, the industrial-scale exploitation and utilization of natural hydrogen remain largely unrealized. Natural hydrogen extraction continues to face significant challenges related to well safety. This paper examines the potential damage mechanisms impacting hydrogen extraction wellbores. It is important to note that current research on hydrogen embrittlement, microbiological corrosion, H_2-cement reaction, and H_2-rubber degradation is insufficient and does not fully address the in-situ conditions of hydrogen wells. Based on the review on the state-of-the-art research and applications, the following recommendations for the futures works are proposed: (1) Mechanisms of hydrogen corrosion of metals under multifactorial effects. In the process of natural hydrogen extraction, metal materials are vulnerable to phenomena including HE, HIC, and HB, alongside corrosion induced by groundwater, CO_2, H_2S, and microorganisms. Traditional materials resistant to hydrogen embrittlement may struggle to cope with the combined effects of these complex factors. (2) Mechanisms of cement failure. Research on the diffusion and transport processes of hydrogen in cement stone at the molecular scale is limited, and studies proving the effectiveness of cement stone in preventing hydrogen escape are lacking. Additionally, the chemical interactions between hydrogen and various types of cement, as well as the transport mechanisms of hydrogen within cement, remain unclear. (3) Failure mechanisms of non-metallic sealing materials. The failure mechanisms of elastomers, such as hydrogen-induced expansion and hydrogen blistering, remain insufficiently understood. Present experimental conditions are inadequate, underscoring the necessity of replicating real downhole environments. The impact of hydrogen on elastomer failure under dynamic wellbore loading, as well as varying hydrogen purity and impurity content, also requires further investigation. Table 2 summarizes the key research areas requiring further attention and provides corresponding recommendations.

While numerous studies have explored the impact of hydrogen on steel, further experimental research is required to understand hydrogen embrittlement in actual subsurface environments and to develop effective hydrogen resistance strategies, such as microstructural modification and advanced coatings. SRBs and other microorganisms can corrode metal wellbore components, producing corrosive gases like H_2S. However, there is currently a lack of long-term anti-corrosion measures for metals exposed to subsurface hydrogen conditions, and metal surface anti-corrosion coatings present a promising solution.

The development of novel cement types with enhanced chemical resistance and sufficient density is necessary to prevent hydrogen leakage through the cement matrix. Insights can be gleaned from research on CO_2-resistant cements; however, a deeper understanding of the mechanisms by which hydrogen affects cement performance and the resistance of additives to hydrogen is imperative. For instance, traditional testing methods, including macro-testing and micro-electron microscope analysis, could be employed to assess how various additive combinations influence structural changes in cement following interaction with hydrogen[115].

Molecular dynamics (MD) simulations are a powerful tool to investigate the hydrogen embrittlement and the interactions between cement matrices and various materials[116]. MD simulations can be employed to identify modified metals with enhanced hydrogen resistance, elucidate the hydrogen permeation process in coatings, and explore the interactions between additives and cement composites in the presence of hydrogen. Recently, researchers have investigated the impacts of additives, including carbon nanotubes, graphene, epoxy

Table 2 | Overview of key points of concern on wellbore safety in natural hydrogen extraction wells and recommendations for solutions

Points of Concern	Recommendations
Mechanisms of hydrogen-induced corrosion in metals under multifactorial conditions and the advancement of effective anti-hydrogen mitigation strategies.	• Experimental investigation of the properties of metals subjected to the combined effects of hydrogen, CO_2, H_2S, and microorganisms under in-situ downhole conditions. • Molecular dynamics simulations serve as a valuable tool for assessing the capability of various metal coatings to resist hydrogen penetration. • Metal coatings represent an effective approach to mitigating hydrogen embrittlement in metals, necessitating validation of their effectiveness under in-situ downhole conditions.
Mechanism of Hydrogen Damage to Cement and Cement Modification Strategies.	• Expand experimental conditions regarding the effects of hydrogen on cement, encompassing temperature and pressure ranges as well as brine concentrations. • Molecular dynamics simulations can be employed to investigate the diffusion of hydrogen in cementite during the extended operation of natural hydrogen wells. • Molecular dynamics can facilitate the elucidation of the interaction mechanisms between hydrogen and various types of cement. • Experimental methods, including macroscopic tests and microelectronic microscopy analysis, can be utilized to examine the structural changes in various additive combinations resulting from their interaction with hydrogen in cement. • Conduct an experimental investigation into the long-term changes in the mechanical properties of cement containing additives under in-situ downhole conditions.
Failure Mechanisms and Modification Measures for Non-Metallic Sealing Materials.	• Investigate the degradation patterns of rubber and other sealing materials induced by hydrogen exposure under in-situ downhole conditions. • Extent of elastomer degradation induced by hydrogen exposure in conjunction with pressure cycling, compression, and wear. • Identify more effective fillers to enhance the hydrogen resistance of elastomers.

resin, and nano silica, on cement properties using MD simulations, yielding a range of significant findings[117]. However, research on the interactions between hydrogen and various types of cement using MD simulations remains in its nascent stages. Therefore, investigating the hydrogen resistance of various additives, such as synthetic polypropylene fibers, graphite nanoparticles, and other engineered materials using MD simulations, could facilitate the discovery of more effective additive combinations for mitigating hydrogen corrosion. Rubber packing presents a promising solution for addressing the failure of downhole elastomers, necessitating further experimental and simulation research to validate its efficacy.

In recent years, machine learning has gained considerable attention for establishing relationships between inputs and outputs. For instance, Piro et al. utilized neural networks to predict changes in the compressive strength of concrete after the addition of carbon nanotubes[118]. To ensure the well safety in natural hydrogen extraction, artificial intelligence (AI) could play a pivotal role. AI may be employed to identify metals and cement additives with superior resistance to hydrogen embrittlement and to predict microbial corrosion throughout the lifecycle of natural hydrogen wells[119].

The Excessive accumulation of annular pressure caused by cement degradation and tubing leakage directly poses a severe threat to well safety. Addressing excessive annular pressure buildup requires investigating the root-level, long-term effectiveness of various anticorrosion techniques and assessing the post-corrosion performance of metal components under in-situ downhole conditions. While approaches like self-healing cements have been explored to reduce overall cement ring permeability and mitigate annular pressure, careful consideration is needed for potential hydrogen-induced cement damage[120]. During the long-term operation of natural hydrogen wells, significant safety and environmental risks are risen due to the leakage through the casing-cement-borehole interface. Laboratory-scale experiments and simulations provide potential solutions for enhancing well safety by exploring sealing methods and identifying materials that improve bonding strength at the cement interface, such as the incorporation of nanoparticles into cement formulations[121].

Hydrogen energy has increasingly integrated into various aspects of society, forming a progressively robust hydrogen energy industry chain that encompasses renewable energy-based hydrogen production via electrolysis, hydrogen fuel cells, and hydrogen-powered vehicles[122]. The exploration and utilization of natural hydrogen align with the global trajectory of energy development. Hydrogen energy has been incorporated into numerous European Union policies and is anticipated to receive further support through forthcoming legislative initiatives. However, as of now, no established standards or regulations specifically govern the extraction of natural hydrogen, nor are there comprehensive guidelines for underground hydrogen storage technologies. The existing regulations for natural gas extraction can serve as a reference model. Future legislation concerning natural hydrogen extraction should prioritize the safety of extraction wells and related matters, including site selection for hydrogen wells, the gas extraction process, monitoring protocols, and post-closure action plans. Furthermore, future regulatory frameworks must address the potential for hydrogen leakage from wellheads at certain rates[123].

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B.J.S.: Conceptualization, Design, Methodology, Writing - Original Draft, Writing - Review & Editing, Supervision, Funding acquisition. M.J.Z.: Conceptualization, Design, Visualization, Writing - Original Draft, Writing - Review & Editing. Q.S.: Conceptualization, Design, Writing - Original Draft, Writing - Review & Editing. J.Z.: Validation, Writing - review & editing. G.H.S.: Writing - review & editing.

Competing interests

The authors declare no competing interests.

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